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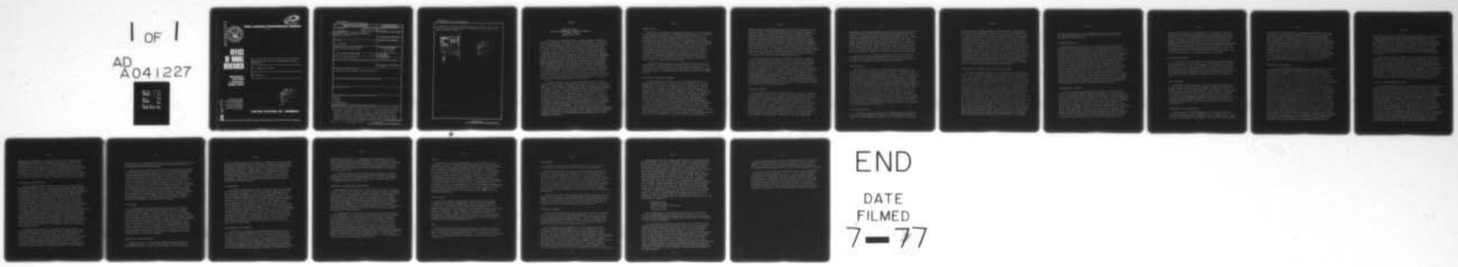

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OFFICE OF NAVAL RESEARCH

FROM SOUP TO NUTS--THE VIIth INTERNATIONAL CONGRESS ON RHEOLOGY

E. A. KEARSLEY, ONR TOKYO

28 DECEMBER 1976

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER C-32-76	2. GOVT ACCESSION NO. (14) ONRL-C-32-76	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) FROM SOUP TO NUTS--THE VIIth INTERNATIONAL CONGRESS ON RHEOLOGY (7th).		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) E. A. KEARSLEY (9) Conference rept.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Office of Naval Research, Tokyo		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (12) 24p.
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Branch Office London Box 39, FPO New York 09510		12. REPORT DATE (11) 28 Dec 1976
		13. NUMBER OF PAGES 17
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Rheology
Polymers
Plastics
Fluid Mechanics
Viscoelasticity

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Brief summaries are given of many of the 270 papers presented and an effort has been made to develop an overall impression of what is going on in rheology these days. The report is meant to serve as a *Guide Michelin* to the tourist travelling through the Proceedings. Topical coverage includes constitutive equations for polymers, chrystalline polymers, rubber elasticity, dilute solution theory, extensional and convergent flows of melts and solutions, chemorheology and aging, birefringence in polymers, block polymers, thermodynamics of viscoelasticity, rheological fluid mechanics, new devices and

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and measurement techniques, technological polymer rheology, melt fracture, failure of plastics, drag reduction, biorheology, granular media, metals, paper and cloth, and gases.

C-32-76

FROM SOUP TO NUTS --
THE VIIth INTERNATIONAL CONGRESS ON RHEOLOGY,
Gothenberg, Sweden,
August 23 to 27, 1976

It never fails to surprise me when, as often happens, a reputable fellow scientist asks, "Just what is this 'rheology' stuff?" For the benefit of such innocents, let me begin by explaining that literally rheology means the study of flow, but that it has come to mean something broader, the study of the deformation or other mechanical response of materials to stress or force. The whole idea of rheology as a distinct discipline dates only to 1929, and as late as 1948 the First International Congress on Rheology took place in Holland. Yet the VIIth International Congress on Rheology, held recently at Chalmers University of Technology, Gothenberg, Sweden, drew 450 scientists from all over the world to hear some 270 papers on every conceivable aspect of rheology (and some almost inconceivable). Had the organization of the Congress not benefitted from the world-famous Swedish engineering skills, the net effect would have been sheer bedlam. Even such skills, however, could not bypass the occasional scheduling of five simultaneous lectures and a poster session. In such circumstances, it is clearly impossible for an individual to audit more than a small fraction of the offerings. To offset this problem, the organizers had managed to persuade virtually every contributor to submit a brief paper covering his presentation, and a printed and bound Proceedings was awaiting the arrival of each participant. Armed with my personal copy of the Proceedings and with assorted notes scribbled in darkened lecture halls on the backs of envelopes, I will essay an account of the Congress.

By a small informal survey, I have established that less than 10% of the participants would even acknowledge being rheologists. The dominant group, as at all Rheology Congresses, was primarily interested in polymers--polymer physics or chemistry, polymer processing including molding, extruding or forming of plastics, the chemical engineering of polymer handling and, of course, biopolymers. However, significant numbers, perhaps half of the participants, dealt with other materials: soil, cement and concrete, suspensions, slurries, gels, powders and granular materials. A bevy of mathematicians treated the problems of symmetry arising in the description of materials or calculated complex flows. One paper (the late Scott-Blair would have classified it as "psychorheology") compared people's perception of softness and springiness of a spring and dashpot device to the parameters of the device (Drake and Jonsson). Such a wide range of subject matter is to me an awe-inspiring thought. To cope, I will group more or less related blocks of papers as if they were isolated symposia within the Congress. If an occasional paper is badly grouped I hope I will be forgiven. References to author affiliations are often omitted on the assumption that interested readers will consult the Proceedings which are referenced in the closing section of this Report.

OPENING SESSION

The Congress opened with all participants gathered in a plenary session at Götaplatsen Concert Hall for a charming welcoming address by the President of the Gothenberg City Council (who had obviously been briefed on what rheology was, but was understandably amazed at the range of application.) The participants were further welcomed in short addresses by the Rector of Chalmers University of Technology (the host institution) and by Professor Josef Kubát, the organizer of the Congress. Professor Odqvist then delivered a short reminiscence of three prominent rheologists, Janacek, Reiner and Weissenberg, who had recently died. Bob Marvin, Honorary President of the Congress, then gave a survey history of the International Committee on Rheology, whereupon Herschel Markoviz delivered a centenary lecture on Ludwig Boltzmann and his principle of superposition. I was amused to learn that at the time of Boltzmann's publication, Oskar Meyer (whose own theory was competitive) objected that "the theory was not based on atomic hypothesis." One often hears the same complaint a hundred years later, though no longer directed at Boltzmann.

Following the opening session, the Congress moved to the University and divided into parallel sessions scattered among five lecture halls and a poster room. For some people this may have posed no problem, but with simultaneous sessions to choose from entitled Theory, Polymer Melts, Polymer Solutions, Fluids, a polymer rheologist found himself faced with an awkward decision.

CONSTITUTIVE EQUATIONS FOR POLYMERS

A central problem of rheology is to find methods of inferring the general mechanical behavior of materials from a reasonable set of specific measurements. The practical importance of this is obvious; for instance, a manufacturer of plastic parts would like some simple tests to tell him how the pellets supplied to him will respond to his complex molding and forming process and how strong the resulting part will be. There were, therefore, quite a number of papers dealing with some aspect of constitutive equations to be used on polymer melts solutions, and amorphous polymers. Roughly speaking, this set of papers could be again divided into three groups, those based on a phenomenological approach, those addressed to the molecular parameters and their correlation with mechanical behavior, and those concerned with the connection between the other two approaches. In recent years, the rheology of solutions and melts has turned to so-called "hereditary" phenomenological models in which the present state of stress depends on the history of the past deformation of the fluid. An invited talk by K. Osaki of Kyoto surveyed the substantial work done in his laboratory in distinguishing by experiment among the various hereditary models. Since I have reported on much of this work recently in the ONR Tokyo Scientific Bulletin, I will only add here that further results with birefringence

measurements were reported at this time and that they confirmed the earlier results. Several contributed papers developed or examined rheological relations, that is, relationships among the data of different experiments which distinguish particular constitutive equations (Chang, Kearsley, Pedersen). There was a paper demonstrating that the BKZ model had good predictive powers for solid polyethylene in torsion, although the theory was used in a modified form for which more than simple stress-relaxation data are needed to characterize materials (Zapas). Other papers reported shear and extensional data on low-density polyethylene using a differential Maxwell-Oldroyd model (Acierno *et al.*), and pointed out that for certain experiments the data do not distinguish between the BKZ model and a modified Lodge model (Phillips). The Lodge model is an early model of polymer solution behavior which is based upon taking account of the making and breaking in shear of "bonds" between the long chain molecules. The material therefore behaves like rubber, but with temporary cross-links.

Two invited papers, by Ziabicki and Schurz respectively, summarized the main features and special consideration of the moleculor theories of inter and intra-molecular interactions. Ziabicki used the term "condensed polymer" systems and distinguished three regions of behavior associated respectively with isolated coils, overlapping coils and a more-or-less continuous entangled network between molecules. Schurz, of the University of Graz, proposed the idea of a "network solution" for concentrated solutions and melts of polymers. In this approach the molecular concepts of dilute solutions theory are replaced with corresponding network concepts--thus entanglement density replaces molar concentration, entanglement spacing replaces molecular end-to-end distance, etc. The idea of penetration between polymer chains plays a big role. A number of contributed papers described theoretical and experimental efforts on these problems (Roberts and O'Brien, Klein and Kulicke, Enyiegbulam and Hourston) and on the Lodge model mentioned above (Marrucci and Acierno, Ronca, Krozer).

CRYSTALLINE POLYMERS

Most polymers encountered in this age of plastics are in a crystalline or semicrystalline state. The crystalline structure of polymers, however, is quite different from that of inorganic or low molecular weight material. Generally, cyrstalline polymers contain lamellar micro crystals, often in spherulitic structures, sometimes separated by amorphous material. Depending on the thermal or deformation history of the polymer, quite different morphologies can result. The mechanical properties of the plastics are therefore commonly studied in terms of morphology. Takayanagi, for instance, presented a study of polyethylene sheets oriented by rolling and compared them to extruded polypropylene sheets. Mechanical measurements had been made to reveal the orientation effects and x-ray scattering was used to monitor the crystallites. The role of the tie molecules which extend between crystallites was elucidated in this study (Takayanagi

and Yamada). Another paper examined the shrinking on heating of stretched films of amorphous and crystalline polyethylene terephthalate (PET) and of Nylon 6. The role of recrystallization was pointed out (Pals). Polyethylene was studied by dynamic x-ray diffraction (Kawai *et al.*). A theory of cold drawing using concepts of plasticity was tested on PET fibers (Vanicek). A particularly interesting paper discussed tensile tests on samples made with narrow molecular weight distributions of polyethylene. Modulus, yield stress and strain dependence on crystallinity and density of the samples were shown. Stress at breaking showed a maximum with respect to molecular weight (Fulmer and Horowitz). In another paper a comparison of branched and unbranched butadiene-acrylonitrile copolymer was used to relate strain hardening to branching of the molecules (Nakajima).

Roger Porter, in an invited talk, discussed the work at Amherst on the extrusion of high density polyethylene by high pressures. In this process a crystal-crystal transformation occurs producing a highly oriented extrudate with extremely anisotropic mechanical properties.

RUBBER ELASTICITY

The remarkable springiness of stretched cross-linked polymer is explained by the classical theory of rubber elasticity in terms of the statistical mechanics of vibrating networks of chains. It can also be applied to the description of uncrosslinked polymer solutions or melts by exploiting the concept of transient entanglements or temporary links. A. S. Lodge is the author of a celebrated model of elastic fluids based on these ideas. At this Congress, he delivered an invited lecture examining the existence of a unique stress-free shape for the Gaussian network of rubber elasticity theory. Other contributed papers also treated questions of rubber elasticity; the effects of entanglements and dangling ends (Valles and Macosko), the use of generalized strain measures (Chang *et al.*, Seth), a computer study of the relaxation of a lattice model (Rotne and Heilmann), the elastic behavior of plasticized polyvinyl chloride (PVC) (Kazama *et al.*) and examination of polybutadiene networks cross-linked in extension (Kramer, Carpenter and Ferry). In this last paper the authors were able to explain the results with a two-network model composed of a purely classical network corresponding to the irradiation cross-links and a non-classical network (Mooney-Rivlin form) corresponding to the original material. The inference is that the classical theory works very well for that part of the elasticity ascribable to permanent cross-links.

DILUTE SOLUTION THEORY

A statistical mechanical model is also commonly used to describe the behavior of dilute solutions of polymers. An invited talk was given by Bird, who with coworkers has been very active in developing a phase-space

kinetic theory of bead-spring models of dilute solutions. Hydrodynamic forces of the bead, Brownian motion and spring forces between beads are all incorporated in the model. What is very nice about this work is that the material functions of a rheological equation of state can sometimes actually be calculated, giving an explicit connection between rheological measurements and molecular constants of the model. A surprising point is that a bead-spring model in the stiff spring limit does not give the same results as a bead-rod model. This fact excited much talk among the *cognoscenti* on the problem of which result was "correct." The answer seems to depend on the purpose of the proposer. Contributed papers on associated work included a generalization of the Rouse-Zimm theory to account for entanglements (Shen *et al.*) and an analysis of a bead-spring model modified to account for details of large distortions of the chain (Hinch). Modifications of the Rouse-Zimm model of a dilute polymer solution were presented (Takserman-Krozer). The helical structure of amylose-iodine complex was investigated through dynamic measurements of visco-elastic properties at ultrasonic frequencies (Amari *et al.*). The shear thickening of polyethylene in decalin near the theta temperature was examined and shown to be a very complex phenomenon (Wolff and Layec-Raphalen).

EXTENSIONAL AND CONVERGENT FLOWS OF MELTS AND SOLUTIONS

The usual methods of spinning a polymer fiber involves a converging flow at a die followed by extension of the extruded fiber and finally wind-up on a reel. Extensional behavior of a polymer is often quite different from its shear behavior. Converging or diverging flow is a complex phenomenon intermediate in character between extension and shear. An invited talk by H. Giesekus described the secondary circulations in such converging flows and some of the instabilities that can arise. In contributed talks on extensional flows, an apparatus was described for measuring extensional flow of polymer melts (Metzner *et al.*), measurements of suspensions of glass beads in polyacrilimide solutions were reported (de Cindio *et al.*), elongational behavior of low-density polyethylene was described (Laun and Münstedt), low and high-density polyethylene were compared in extensional flow (Shaw), an apparatus to measure extensional behavior of flat tapes was described (Miller and Shaw), and extensional flow of polystyrene melts was discussed (Metzner *et al.*). Some years ago, R.J. Gordon devised a clever way to study extensional rheology of low-viscosity fluids. Observing the vortex formed as a tank of fluid empties through a drain, he noted that a good "drag reducing" polymer tended to inhibit the vortex formation. New results presented here suggest that the effect is due to a large extensional viscosity (Chiou and Gordon). In related work, entrance pressure and flow-rate measurements of flows through an orifice were combined with measurements of flow angles (made visible by dye injection) for so-called "wine glass stem" flows to finally produce measurements of extensional viscosity (Balakrishnan and Gordon). Changes of pH had a surprisingly

big effect on the behavior of polyacrylamide solutions in this work. A rheo-optical study of the stresses along the axis of a flow into a duct was presented (Podolsky *et al.*).

CHEMORHEOLOGY AND AGING

Most constitutive equations deal with materials which in some sense have permanent well-defined properties. A more difficult subject is the description of materials which "age" by undergoing some irreversible (usually chemical) change. "Chemorheology" is a term loosely used for this sort of study. An invited paper by A. Silberberg described a linear viscoelasticity theory designed for treating chemorheological problems. In another invited paper, Struik showed the similarity of aging effects among a wide range of glassy materials, polymers, bitmmn, shellac, sugar, lead, and even cheese. In contributed talks, the thermal stability of PVC was discussed (Abbos and Porter), time effects of polyurethane after annealing were treated (Wilkes *et al.*), the mechanically enhanced aging of polymer glasses was discussed (Sternstein and Myers), the cure-reaction kinetics of epoxy resin systems was described (Ryan and Kamal), a formal theory of materials with spatial-temporal symmetries was presented (Morgan), a generalization of linear visco-elasticity suitable for describing a gelling material was compared to experiment (Roscoe), and a thermo-chemical theory of non-linear stress relaxation was applied to Viton rubber (Nunziato and Curro). Another paper described the application of the Weibull distribution to a statistical theory of aging (Fong). The method was applied to paper and natural rubber. These papers represent the substantial results of an increasing and penetrating attack on the difficult problems of aging materials.

BIREFRINGENCE IN POLYMERS

A sort of rheological philosopher's stone might be termed a "stress-meter," a device which would measure all the components of stress in the interior of a strained solid or shearing flow without in any way interacting with the deformation. Optical birefringence has always fascinated rheologists because for some materials and situations it may offer a way to approximate a stress-meter. Although birefringence techniques are difficult, the rewards are potentially great. An invited talk by W. Philippoff suggested the use of "isopachic fringes" obtainable through laser holography to measure the pressure distribution in fluids. These data combined with the conventional birefringence measurements should, in principle, give the complete stress tensor. Experience with a Newtonian fluid suggests that the method has promise, although allowance must be made for temperature effects Contributed papers dealing with birefringence in fluids included a study of the build-up of stress in sheared polystyrene which showed the Lodge model to work at low shear rate (de Cindio *et al.*), a theory of polymer solutions in

optically active solvents using complex 2 x 2 Jones matrices (Kaye and Syrotiuk) and a comparison of birefringence of polyethylene melts in flow through a slit to the that of gelatine elastically deformed in the same slit (Arai *et al.*). Two papers dealt with flow birefringence of milling yellow, one examining the usefulness of this method for studying fluid mechanics (Truchasson) and one showing a strong non-linear wavelength dependence of the birefringence for this material (Krishnamurthy and Pindera). An examination of rubbery polybutadiene in extension showed that both the stress and the birefringence can be reasonably represented as a function of deformation by the so-called Mooney model (Nordermeer and Ferry). The two Mooney "constants" are, of course, functions of time, but their relaxations are separated in time by about two orders of magnitude.

OTHER EXOTIC TECHNIQUES

An assortment of "exotic" physical techniques was proposed or applied. Applications of electron spin resonance to polymer physics were discussed in an invited talk by Lindberg and Törmälä. In a contributed talk, the method was used to look for radicals formed by chain scission in fracture of polymers (Kausch). Segment mobility of polymers was studied by fluorescence depolarization (Chapoy), and infrared dichroism was used on glassy polycarbonate (Jansson and Yannas). The effects of electric fields on the viscosity of polar liquids was examined in another talk (Babchin *et al.*).

BLOCK COPOLYMERS

With modern chemical techniques, it is quite possible to form long chain polymer molecules with specific segments polymerized from different monomers. These so-called "block copolymers" are very illuminating to polymer physics as well as technologically useful materials. Various papers at the Congress dealt with these materials. They included a comparison of copolymers of polyolefins with corresponding blends (Piloz *et al.*), a study of an ethylene-propylene terpolymer (Greco *et al.*), a study of styrene-butadiene copolymer in solution (Enyiegbulam and Hourston), an examination of the mechanical properties of polyester-polyurethane fibers (Ferguson and Ahmad), and a look at the adhesive behavior of copolymers (Gerard *et al.*).

THERMODYNAMICS OF VISCOELASTICITY

Everyone agrees on the thermodynamics of an ideal gas (after all, we learned that at our mother's knee), but when it comes to non-linear viscoelastic substances such as polymers, then the arguments begin. Thus, the three invited talks on thermodynamics stirred up considerable comment.

G. Astarita of Naples emphasized the importance that constitutive assumptions have in relation to the assignment of fractions of the stress power to dissipation and to elastic energy and other energy storage modes. Müller gave a most interesting talk showing the results of experiments with a calorimetric apparatus following the heating during the stretching of various materials. Necking phenomena and stretch-induced crystallization and melting were observed. Such data are rare and badly needed for progress in understanding thermodynamic questions of material behavior. Oldroyd discussed an idealized model imagined to have several mechanisms with widely separated characteristic times such as would show apparent equilibria on different time scales. When this separation of equilibria is reduced without otherwise changing the theory, there results a non-linear equation of state, invariant in form and satisfying the second law of thermodynamics for irreversible changes. It was proposed as a prototype for study. Further thermodynamics appeared in two contributed talks which discussed kinetic theories of thermorheology (Bohlin *et al.*, Lechenthal).

RHEOLOGICAL FLUID MECHANICS

A well-represented field of endeavor might be characterized as "rheological fluid mechanics." Papers in this field ranged from highly mathematical calculations to experimental flow studies. The "in" subject seems to be finite-element calculations. The finite-element method of calculating a flow is based upon the idea of dividing the flow field into small volumes and finding solutions in each volume which match together to approximate the global flow. The volumes can be tailored to the geometry of the problem, and computation effort can be distributed most efficently between approximating the condition of incompressibility or other geometric contraints and satisfying the stress equations. Roger Tanner, in an invited talk, gave a good survey of his experiences in applying the method. The rheological models he used were generally very simple power law models or second-order fluids where normal-stress effects played only slight roles. Among others, the very difficult die swell problem had been done. This is a free-surface problem and thus is far from trivial. The method is clearly of great interest and many contributed papers on the subject were offered. Problems treated in contributed papers included impact on the end of a viscoplastic bar (Davids and Wenner), flow of a fluid with shear-dependent viscosity past a sphere (Adachi and Yoshioka), unsteady axial flow of a Oldroyd fluid between two concentric annuli (Akay and Kaye), flow of a second-order fluid across a slot (Malkus), and a complex problem related to turbines (Geymonat and Raous). The "broken section" method of Ito also appears to me to be related to finite-element calculations. Methods other than finite-element were used in other rheologically interesting flow problems: the flow of a second-order fluid in periodically convergent-divergent channel (Pellerin and Thirriot), the wall effects of a falling-ball viscometer with viscoelastic fluid (Sigli and Coutanceau), the stress singularity at the leading edge of a flat plate in a viscoelastic flow (Caswell), a Bingham fluid in a rectangular pipe with rectangular core (Panagiotopaulos), a material

with a yield stress in a curved channel (Astin), a power-law fluid oscillating in a pipe (Ly and Bellet), flow between eccentric rollers (Ulbrecht and Deysarkar) and pulsatile flow in a porous channel (Bhatnagar). By use of momentum balance, upper and lower bounds were calculated for die-swell of a viscoelastic material (Huilgol), a criterion was derived for determining when a flow results in a constant stretch history and a practical method of applying the criterion was displayed (Huilgol). The effect of viscoelasticity on flow into the entrance of a capillary was calculated, and it was shown that, depending on the values of the viscoelastic parameters, the entrance region could be larger or smaller than for a Newtonian fluid (Tan and Tiu).

The Weissenberg effect is observed when a rotating rod is dipped into viscoelastic fluid. The fluid climbs the rotating rod. This is a classical demonstration of normal stress effects resulting from tension along the flow lines of the shearing fluid. A calculation of the Weissenberg effect was given and compared to experiments with STP, the much advertised automotive engine additive. Although the calculation is not easy, in this case it was well done judging by the excellent fit with experiment. Other experimental studies include Hele-Shaw flow past a cylinder (Schmidt) and a comparison to the theory of Chang of the start-up flow of a fuel oil and of a suspension (Parker *et al.*). A study of die-swell using hydrogen-bubble visualization techniques revealed that a disturbance propagates upstream into the die to a distance of the order of the diameter of the die (Higashitani *et al.*).

NEW DEVICES AND MEASUREMENT TECHNIQUES

A large number of new devices or methods were presented at this Congress. A rheometer for biaxial deformations utilizing the inflation of a molten polymer sheet by pressurized inert liquid was presented (Denson and Hylton). A device for measuring the high frequency limit of dynamic data on dilute polymer solutions was described (Koh and Birnbaum). An ultrasonic viscometer based on wave propagation at 1.25 MHz was described (Hubeny), and measurements of ultrasonic absorption and phase velocity in detergent solutions were reported (Gravsholt and Bjørnø). Examples of data taken with a fixture for applying compression to a sample in a Rheovibron was described and data shown (Murayama). A viscometer for molten glass was described (Merle and Truchasson). The Rheotron rotational viscometer was used with polymer melts (Heinz and Rothenpieler). Measurements of transients by a Rheometrics device were compared with Meissner's results taken with a Rheogoniometer (Macosko and Morse). The problems of cone and plate geometries were examined with a specially designed apparatus (Gleissle). A device for measuring the Weissenberg effect was presented (Dealy and Vu), and the use of computers in viscometry and tensile testing was described (Hansson *et al.*, O'Brien and Parnaby). Two- and four-roller mills with dye injection were used to examine extensional flows in polymer solutions (Broadbent), and a new method of measuring the second normal stress difference was presented

(Higashitani and Iwamoto). A torsion pendulum method of studying fiber-reinforced polymer was presented (Kambe *et al.*), and a technique called "thermostimulated creep," TSC, was discussed (Monpagens *et al.*). In a most interesting paper, the jet-thrust method of measuring normal stresses at high shear rates was combined with special nozzle shapes to study biaxial stretching (Oliver and Ashton). A method of evaluating the mechanical properties of a viscoelastic fluid from the formation of Taylor vortices was examined (Fong and Jones). The method has been worked out for a third-order fluid, an Ericksen anisotropic fluid and an Oldroyd fluid. A method of using thin jets to measure dynamic surface tension was presented (Ronay).

TECHNOLOGICAL POLYMER RHEOLOGY

A very substantial number of papers considered specific technological problems of polymer processing. Invited papers by Pearson, Tadmor, Meissner and Han dealt with this area. Pearson emphasized the point that diffusion and relaxation times of polymers are often significantly longer than processing times and hence that non-equilibrium configurations and "supra-molecular" structures may govern the relevant rheological behavior. Tadmor urged the theoretical analysis of processing in elementary steps which could be considered in terms of the basic physics. He saw this as a route to creative engineering in processing methods. Meissner has recently moved from industry (BASF) to the Institute of Technology, Zurich. He gave a review of instruments available for various shear and extensional measurements on polymer melts, showed some results and pointed out that the usefulness of capillary viscometry is quite limited. A case in point is the well-known IUPAC study of three low-density polyethylenes which were indistinguishable by standard industrial tests but when blow-molded showed large differences in procesaibility and end properties. Han gave some results of extrusion, injection molding and fiber spinning of blends of calcium carbonate-filled polypropylene with polystyrene. Photomicrographs of extrudate and spun fibers and measurements of mechanical properties of molded samples revealed a complex pattern with respect to blending ratio. Since some of the samples were four-phase systems (high-impact-strength polystyrene is laced with rubbery particles), this result is not surprising. Such are the materials of technology, however.

An interesting new process was reported by Turner and Cogswell. In this "Fibre Foam" process, the fibers suspended in a thermosetting plastic become highly crimped on extrusion through a die, but expand again after extrusion to produce an irregular open-cell structure with many uses. Contributed papers on fiber-spinning included an identification of a certain spinning instability as one caused by "melt fracture" rather than "draw resonance" (Mhaskar and Shah), and a study of the spinning of fibers of polyethylene, polypropylene and polyamides (White *et al.*). Concerning extrusion, there were papers on calculation of residence time (Ingen Housz), calculation of the co-extrusion of immiscible polymers to form a sandwich

sheet (Ito *et al.*), calculation of residual stress in extruded pipe (Gorrisen) and measurements of pressure relaxation at the die wall after extrusion of styrene butadiene copolymer (Le Blanc).

Among the papers on injection molding were an observation of two types of mold filling, flow-smooth filling and jetting, whose occurence depended upon the die-swell properties (White *et al.*), a paper on the advantages of high-pressure injection molding (Djurner and Rigdahl), an account of a method of compensation for volume effects to be used in short-volume control (Hunkar) and an outlined program of study of the injection molding of short-fiber thermoplastic composites (Charrier and Skatchkov). The theory of calendering was considered by Ehrmann *et al.*), and Ahuja of Xerox discussed the effects of residence-time/relaxation-time ratio on cold-rolling of polymer films and applied the idea to a problem of xerography. Wagner gave a detailed analysis of the film-blowing process taking into account the rapid cooling that normally takes place between die and solidification point. Problems of heat transfer and viscous heating in polymer processing were discussed in two papers (Winter, Matsui and Bogue). Three papers, one invited, dealt with the problems of lubrication (Hutton, Godfrey, Trapeznikov and Fedotov). Two papers were concerned with the effects of plasticizers (Kumanotani *et al.*, Titomanlio and Rizzo).

MELT FRACTURE

In a movie some years past, Monsieur Hulot, working in a plastics plant, encountered an extruder which hiccupped periodically to produce an extrudate looking like a string of sausages. Some such phenomenon actually occurs in polymers too rapidly extruded, but it is not so funny as in the movie. N. Bergem's invited lecture on extrusion anomalies showed detailed pictures of the screwthread-like surfaces that can occur on extruded fibers in some circumstances. He gave an account of this and other phenomena often lumped together as "melt fracture." Bergem proposed that a sort of yield stress for entanglements accounted for these phenomena, and the proposal was compared to other explanations. Contributed papers on this subject compared the critical conditions for melt fracture in capillaries to the critical conditions for melt fracture in slits (Vlachopoulos and Chan), determined that viscous heating was not the primary cause of melt fracture (Ho, Denn and Anshus), and examined the consequences of a thin lubricant layer at the die wall (Uhland).

BREAKING AND FAILURE OF PLASTICS

A number of papers can be collected under the heading of breaking or failure of plastics. A "flaw spectrum theory" was developed in one paper (Rosenthal and Sternstein). In this theory, flaws are modelled

as tiny ellipsoidal holes and the effects of deformation on the orientation and shape of these ellipsoids is reflected in a changed spectrum of flaws. The theory was applied to some data of Retting for drawn polystyrene sheet. Another paper developed an energy criterion for fracture and applied it to polymethyl methacrylate (PMMA) (Brüller). The Charpy impact test was shown to be essentially a rapid bending test for PMMA (Tak). Other contributed talks included a study of delamination effects in the failure of thermosetting laminates (Ito *et al.*), the study of a brittle ductile transition in impact tests on polycarbonate (Ballabio & Berizzi) and an examination of Izod tests on matched ABS samples (Rink *et al.*) and on polycarbonate (Hartmann and Lee).

DRAG REDUCTION

At the first International Congress on Rheology, almost 30 years ago, the "Toms effect" was presented. In this phenomenon, the addition of very small quantities of polymers to fluids reduces the hydrodynamic drag of turbulent flow, sometimes by almost an order of magnitude. Because of the large number of parameters involved in the effect, progress in understanding it has been slow, and it is my impression that a proper mechanism for the effect has still not been established. Several papers on this interesting and important phenomenon were presented at this Congress. A thermodynamic basis for turbulence was proposed (Hlaváček and Stanislav), and an examination of the effect of molecular weight on the effectiveness of drag reduction was reported (Hlaváček *et al.*). A very interesting study of the optimization of drag reduction with respect to the rate of injecting polyox was reported (Lang). In this study, a slotted plate was used and the distribution of injection points was varied. Another paper examined drag reduction effects in a turbine, and it was noted that aeration of the fluid plays a significant role (Ulbrecht *et al.*). A curious effect was reported for the flow in a pipe oscillated axially (Mena and Manero). At a fixed pressure difference, flow rates increased by a factor of 10, apparently in laminar flow.

BLOOD RHEOLOGY AND BIORHEOLOGY

The activity in biorheology has grown phenomenally in recent years, and there was a good representation of this field. An invited talk by L.E. Gelin described the effects of shock and trauma on blood flow, particularly in the capillary system. Progress in the rheological treatment of medical problems has been fruitful. It was pointed out that some recent statistics on surgical patients showed that hemodilution resulted in a 50% decrease in mortality and thrombo-embolic complications. Contributed papers on the rheology of blood included an *in vitro* study of hystresis in blood flow (Apelblat *et al.*), a model of blood rheology based on effects of red cell concentration and aggregation (Quemada), a study of red cell

sedimentation (Huang *et al.*), a description of a new rheometer for blood studies (Meier & Spinelli), and an examination of the Fohraeus-Linquists effect for oscillatory flow (Singh and Coulter). This term covers a variation of the apparent viscosity of blood with tube size, supposedly due to red cell migration in shear flow. In another intriguing paper, micropipettes were used to deform individual red blood cells to examine their mechanical properties (Missirlis).

In theoretical papers, rheological models were devised for arteries (Stoychev, Sharma and Hollis), and a pulse-propagation method of examining artery walls *in vitro* was proposed (Flaud *et al.*). A model of cartilage was developed viewing it as a porous visco-elastic medium permeated by an incompressible fluid (Lipshitz *et al.*).

SUSPENSIONS, DISPERSIONS AND GRANULAR MEDIA

Suspensions and dispersions have traditionally been of great rheological interest. Studies on such materials at this Congress included: suspensions of TiO_2 in water (Umeya and Kanno), sand-filled polymers (Simenov and Ivanov), rocket propellant, a suspension of particles in polyisobutylene (Dukes and Stenson), and carbon black dispersions (Schoukens *et al.*). Parallels were drawn between the behavior of block copolymers and filled polymers (Münstedt). Three theoretical papers on the statistical mechanical approach to constitutive equations for suspensions were presented (Leal, Buyevich and Shchelchkova, Shmakov *et al.*). Two papers dealt with the effect of flocculation on the rheology of suspensions (Hudson *et al.*, Firth and Hunter). One paper examined the effects of wall slip on the rheometry of slurries and suspensions (Cheng and Parker).

For many materials with discrete structure some sort of micromechanics must be considered. D. R. Axelrad in an invited talk described an approach to such problems which treats microstructure through random variables. In a contributed paper, it was pointed out that such ideas of microheterogeneity would be necessary to describe cross-linked polymers for which the cross-link sites are comparable in size to the chain lengths between cross-links (Katz and Zewi). An invited talk by L. F. Nielsen described the rheological considerations necessary to understand creep in concrete. Similar materials considered included clay (Pusch), cement pastes (Jones & Brindley, Ivanov and Stanoeva), fiber-reinforced concrete (Komlov) compressed concrete (Béres), asphalt concretes (Sharma and Kenis), granular thermoplastics (Thirriot and Sengelin), and cohesive powders (Bache). A visco-elastic analysis of paving systems was presented (Battiato *et al.*) and an examination of the properties of road bitumens (Isayev *et al.*).

METALS

An interesting and promising development at this Congress was the appearance of a significant number of papers on metals and other inorganic crystalline materials. An invited paper by Zarka, Casier and Engel advocated the derivation of constitutive equations for visco-plastic behavior of metals starting from considerations of the microstructure. In this spirit, a contributed paper compared a model of creep in crystals to data for GaSb (Feltham). A theory of dislocation movement connected with an activation volume was presented (Olafsson), a mathematical theory of elastic-plastic rate dependent material was developed (Durban and Baruch), a theory of intergranular fracture was presented (Brothe), and the concept of relaxation spectra was applied to metals (Varchon *et al.*). Experimental papers included a viscometric study of tin-lead slurries (Joly and Mehrabian), a study of super-plasticity of an aluminium-copper eutectic in compression (Padmanabhan and Davies) and a study of the surprisingly large effect of nickel coating on the creep of tungsten wire (Warren *et al.*). A paper comparing the rheological behavior of metals to many other materials (Kubát *et al.*) has already been mentioned.

PAPER AND CLOTH

A surprising number of papers were on some aspect of the rheology of papers or other fibrous 2-dimensional systems. Two talks developed probabilistic microrheological approaches to the rheology of paper (Alrad *et al.*, Fong). The second of these applied Weibull statistics to a chemorheological problem. Another pair of papers examined fibrous 2-dimensional systems in compression: paper (Engmann *et al.*) and mats of glass fiber (Thirriot and Onder). A paper by Kubát *et al.* observed similarities in the behavior of metals, polymers, cellulose and paper. The creep of cloth was examined in another paper in which the applicability of time-temperature superposition was demonstrated (Minster and Berka). A theory of a porous 2-dimensional medium was developed (Sobatka).

GASES

Three papers on viscometry of gases were given. Capillary viscometry was covered on Rankine type viscometers (Meerlander) and an absolute measurement of the viscosity of nitrogen (Kurase *et al.*). Nitrogen is frequently used as a viscosity standard in gas viscometry. An oscillating disk viscometer for gases with automatic decrement measurement system was also described (Yoshida *et al.*).

MISCELLANEOUS

A variety of papers given at the Congress did not fall easily into the groupings I have made and I mention them here in a random way.

Three papers suggested new ways of treating data--an averaging technique for calculating flow curves (Chmiel *et al.*), a method of using intermittent creep data (Forgacs and Hedvig) and a general treatment of rotational viscometer data (Mischka *et al.*). An interesting paper on inorganic non-metallic glasses related chemical surface properties to hardness (Westwood *et al.*). The Griffith criterion was applied to two parallel but not co-linear edge cracks to estimate tensile strength (Chen). Papers on nematic liquid crystals in electric fields and in temperature gradients were presented (Askar and Cakmak). A study of the effects of pressure on the cellulose acetate membranes used in desalination of sea water by reverse osmosis was given (Jonsson). There was also a paper on nomenclature (Trapeznikov).

Two interesting and unusual presentations discussed the noise associated with rheological processes. Bismith and Tatraux-Paro discussed the waves observable in a rubbery material sliding against a glass plate (Schallamach waves). Klason and Kubat listened to the noise of polymer solutions in a Couette viscometer. They detected a $1/f^{\alpha}$ dependence on frequency, also depending on shear-rate, molecular weight and concentration.

RETROSPECTIVE REMARKS

Between this Congress and the last (Lyon, 1972), the social atmosphere in which science must operate has changed markedly. The oil crisis has had an effect on industrial laboratories, and universities are responding to a new demography and worldwide inflation. I know of rheologists who could not manage support to attend this Congress, and I met some who were attending the Congress on their own. In view of this, the attendance of 450 scientists and 90 guests is almost spectacular.

The arrangements and accommodations for the Congress were superb. Chalmers University of Technology sits on a hill overlooking the city of Gothenburg. It has excellent modern lecture halls conveniently spaced for such a meeting. The dormitory facilities offered deserve special comment. The student rooms we occupied were large, comfortable and beautifully furnished with Swedish modern furniture and private bathrooms. Small kitchens and laundry facilities were also available. I wonder that the students can be persuaded to finish their studies and graduate! On Wednesday afternoon, the whole Congress took an excursion by boat to Fredrikshavn, Denmark. The weather was great and the food was terrific. On Thursday evening, the traditional Congress banquet was held at Restaurant Longedrag. For me this Congress was a first visit and a delightful introduction to Scandanavia.

Innovations of the VIIth Congress included the use of poster sessions and the pre-publication of the Proceedings. Response to the poster sessions was not unanimous. Generally, the audience found it convenient, but the authors were of divided opinions. My own feeling is that certain subjects and authors are ideally suited to this sort of presentation but others are not. The poster sessions certainly offer a way of making tight schedules more flexible and the method is worthy of more experiments. There is no doubt that the pre-published *Proceedings* was widely appreciated. Many auditors appeared at talks, *Proceedings* in hand, and some speakers assumed that equations and graphs were being followed in the text. I found the latter inconvenient, since I chose not to carry the heavy *Proceedings* around with me, but I used it extensively in preparing my plans for the day's sessions. There was perhaps a slight inhibition on what was presented at the Congress because the deadline for publication was necessarily many months earlier. On the other hand, this need not have been, since many authors took advantage of the suggestion that talks could deviate substantially from the published paper. The considerable editorial accomplishment (C. Keason, J. Kubat) in an amazingly short time still surprises me, but mostly I wonder how the editors managed to persuade virtually all of the speakers to submit articles on time. I understand that copies of the *Proceedings* are still available from the Swedish Society of Rheology (Skr.350). The appropriate address is:

Rheology Congress
%Professor J. Kubat
Chalmers University of Technology
Fack, S - 402 20
Gothenburg, Sweden

Many of the papers at this Congress were specific to a particular material through considerations of morphology or chemistry. I can find no simple theme encompassing the Congress. There were, however many papers dealing with general approaches or pointing out similarities in the behavior of widely differing materials.

It is similarities, rather than differences, which form the most surprising feature of rheology--and the most ignored. Until recently, metallurgists were only marginally interested in creep and stress relaxation phenomena because, to a large extent, metals were used at temperatures where such effects posed no practical problems. In the age of atomic reactors and supersonic planes, however, metals are used at high temperatures and at design strength so that these time-dependent effects must be dealt with. Polymer rheologists have learned a good deal about such effects--they have studied these phenomena in polymers for years. On the other hand, the polymer scientists are only beginning to unravel the complex effects of polycrystallinity in plastics--something analogous to the traditional studies of metallurgists. One suspects that the two groups have much to teach each other and that similar parallels could be drawn among many other specialists. Therein lies what is perhaps a principal long-range benefit of these Congresses.

As is customary, a meeting of the International Committee of Rheology was held during the Congress to select a tentative site for the VIIIth Congress. An invitation to hold the next Congress in Naples, Italy, in 1980 was unanimously accepted. Professor Josef Kubát, the organizer of this Congress was elected Chairman of the International Committee on Rheology.

As it turns out, I have spent considerably longer on this review than I anticipated. Had I had the wit to do so, a simple calculation before I started would have shown me that just to spend two minutes skimming each paper in the *Proceedings* would consume about nine hours--before a word was written. Furthermore, I certainly cannot claim to be an expert, or even mildly conversant with the many fields covered. I can only hope my effort will prove of value to the reader, possibly in two ways--by developing an overall impression of what is going on in rheology these days and by serving as a sort of *Guide Michelin* to the tourist travelling through the *Proceedings* of the VIIth International Congress on Rheology.